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GUN TUBE HEATING

PAUL J. CONROY

DECEMBER 1991

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U.S. ARMY LABORATORY COMMAND

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13. ABSTRACT (Maximum 200 words) <p>A one-dimensional gun tube heating model has been coupled to an interior ballistic code. The ballistic code models the two-phase interior ballistic cycle and provides intensive and extensive properties throughout the cycle. At the inner wall of the gun tube, a turbulent boundary layer correlation is used to compute the heat flux to the wall. This correlation incorporates the compressibility of the flow in calculating the Reynolds number and skin friction coefficient. Within the tube wall, the one-dimensional radial heat conduction equation is solved.</p> <p>The model is used to investigate gun tube thermal profiles over multiple firings with variable firing rates for two different weapons. Results are used to describe the transient heating of the gun tube over a long period of continuous firing. Potential firing scenarios are presented and discussed. Numerical results are compared to experimental work performed in the past. An extensive reference list is also included.</p>				
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1. INTRODUCTION

The development of the Advanced Field Artillery System (AFAS), with its high rate-of-fire requirement, has refocused interest in the thermal management of gun tubes, which includes consideration of cook-off of propellants and/or projectiles, tank gun accuracy, barrel wear and erosion, and thermal signature. In the past, investigators have measured gun tube thermal profiles for various weapons and they have employed heat conduction codes to model the gun tube heating (see references). The lack of appropriate boundary conditions at the inner wall surface compelled researchers to use ingenious approximation techniques (Rapp 1990) and curve fitting to produce a history of tube heating during the interior ballistic cycle. One method to produce the inner wall boundary condition was to use thermocouple measurements to compute the heat input to the gun tube along its length. These measurements provided an experimental axial heat input profile which then was used to model other similar systems. This was accomplished by modifying the input profile using a ratio based on the total energy of the charge. This type of model neglects the mechanisms which lead to the development of the thermal profile and, thus, does not allow the model to make predictions for a weapons system significantly different from that used for the model calibration.

Barrel heating is due to forced convection of hot combustion gases, the projectile's sliding friction, and obturator galling. In addition, there may be a significant radiative contribution to the heating in the region of the breech (Leech 1972). Plastic obturators have reduced the galling and sliding friction component considerably. A one-dimensional interior ballistic (IB) code can supply the information which is necessary for computing the interior boundary condition at the wall, given a proper convective coefficient, which must include the effects of pressure, gas velocity, and compressibility of the combustion products both spatially and temporally.

Recently, Chandra (1990) and Chandra and Fisher (1989) have applied an IB code (Gough 1980) to barrel heating. This work utilized the results from IB codes to provide an appropriate inner wall boundary condition to the heat transfer/conduction routine.

2. ANALYTICAL DESCRIPTION

The analysis used by Chandra and Fisher (1990) is presented below. It incorporates a compressible turbulent boundary layer with an arbitrary pressure gradient model (Stratford and Beavers 1961). An equivalent flat-plate length is calculated

$$\chi = \frac{\sum_1^z (P_z \Delta Z)}{P_z} \quad (1)$$

using a Mach number weighted pressure

$$P_z = M^4 \left[1 - \frac{1}{2} (\gamma - 1) M^2 \right]^{\frac{(3\gamma-1)}{2(\gamma-1)}} \quad (2)$$

where

$$M = \frac{u}{\sqrt{\gamma R_g T_g}} \quad (3)$$

The compressible Reynolds number is then computed as

$$Re^* = \frac{\chi \rho^* u}{\mu^*} \quad (4)$$

with the viscosity, $\mu^* = \nu^* \cdot \rho$, computed using a modified form of Sutherland's law (Schlichting 1979)

$$\nu^* = \frac{1.492 \cdot 10^{-6} T^{*1.5}}{145.8 + T^*} \quad (5)$$

having determined the static temperature, T^* , from the reference enthalpy (Chandra and Fisher 1989). The compressible skin friction given by (Carpenter and Klavins 1965)

$$\frac{c_f}{c_{fI}} = [1 + (\gamma - 1)^2 M^2]^{-0.6} \quad (6)$$

is incorporated with Re^* , C_p , μ^* , and χ to create the heat transfer correlation (Chandra and Fisher 1989)

$$Q_w = \left[0.037 \frac{\mu^*}{\chi} Re^{*0.8} \frac{C_p}{C_{pf}} (T_g - T_w) \right] . \quad (7)$$

Thus, the heat transfer coefficient is

$$h = 0.037 \frac{\mu^*}{\chi} Re^{*0.8} \frac{C_p}{C_{pf}} . \quad (8)$$

This system of equations has been shown to work fairly well for short periods of firing (Talley 1989). Due to the boundary at the breech of the gun tube, this velocity-dependent correlation fails to physically represent the rear portion of the gun tube. To correct for this, a turbulent velocity has been introduced into the system. It effectively raises the magnitude of the local gas velocity by using a turbulent Mach number of 0.1 (Chandra 1990).

Leech (1972) has investigated the effects of thermal radiation inside the chamber using a participating medium model. His results indicate that within a few inches from the breech the significant mode of heat transfer is radiation, while farther down the chamber the particles in the developing boundary layer absorb most of the radiation. The incorporation of a particle-laden, absorbing boundary layer is a possible addition to the future version of the model which may reduce the reliance on the turbulent convection and increase the physical accuracy of the model.

The method used for solving for the tube temperature utilizes the one-dimensional radial heat conduction equation

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (9)$$

with the internal boundary condition given as a specified heat flux

$$-k \frac{\partial T}{\partial r} = h(T_g - T_w) \quad (10)$$

and an insulated external boundary. The physical properties of the gun steel are treated as constants throughout the calculation; however, the properties presented by the Mechanical Properties Data Center (Belfour Stulen Inc. 1973) show a reduction in the conductivity and a sharp spike at 1,400 K in the specific heat with an increase in temperature.

The equations are explicitly computed using central differences and the grid has been generated using a geometric factor to account for the radial geometry and the fine grid necessary at the inner wall. An allowance has been made for various materials, such as chrome, to be included in the tube.

The model used in this paper incorporates the one-dimensional NOVA (Gough 1980) IB code to provide the necessary state variables for the calculation of the convective heat transfer coefficient described previously. Typically, the duration of an IB cycle is on the order of 50 ms or less; however, for heat transfer studies, the IB cycle is assumed to be from the time of the first round until the barrel reaches ambient temperature or until the next round is fired. The requirement on the IB code to produce the necessary state variables after shot exit for up to six orders of magnitude in time greater than a typical IB calculation necessitates the use of a open muzzle boundary condition after shot exit. Gough (1980) uses an isentropic (Eq. 11)

$$\dot{M} = A_{ext} \frac{\left[\frac{2g_o}{\gamma-1} - (\gamma R_g T_o) \left[1 - \left(\frac{P}{P_o} \right)^{\frac{\gamma-1}{\gamma}} \right] + 2g_o b P_o \left[1 - \frac{P}{P_o} \right] \right]^{\frac{1}{2}}}{\frac{R_g T_o}{P_o} \left(\frac{P_o}{P} \right)^{\frac{1}{\gamma}} + b} \quad (11)$$

or choked (Eq. 12)

$$\dot{M} = A_* \frac{P_o}{\sqrt{T_o}} \sqrt{\frac{\gamma g_o}{R_g} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} [1. - 0.224y + 0.104y^2] \quad (12)$$

mass flux calculation for either subsonic or supersonic exit flow, respectively, thus allowing the gas flow out the gun muzzle to continue to empty the gun tube. This allows the IB code to compute the thermodynamic expansion cooling, rather than using a linear interpolation to ambient conditions. This calculation can be maintained for about 80 ms, by which time the breech pressure has reached ambient and the NOVA code stops. The other state variables are then brought to ambient through either a conservative linear interpolation or a special exponential function which reduces the state variables to ambient after a short amount of time (about 1–2 s) with respect to the cycle time. The exponential decay function resulted in the prediction of approximately 3% lower inner wall temperatures after 30 rounds at 12 rounds per minute are fired in the 155-mm M199 cannon, using an M203 charge. This implies that a conservative approach will trade a small increase in wall temperature for confidence that the experimental temperature will not exceed the computed values.

Figure 1 presents the flow chart of a conduction calculation using the Chandra and Fisher model. The state variables are stored temporally and spatially in the HTEMP.OUT file, thus creating an IB "signature" for a specific charge. This signature can then be utilized to study various firing scenarios assuming that the feedback to the IB calculation is small. The heat transfer and conduction code XB is used to make various scenario studies with the signature file as an input along with the desired scenario defined in the input deck XB.IN.

The output of this IB code for one round is then used in a separate uncoupled interpolation and heat transfer/conduction routine. Given the history of one round, this stand-alone routine allows the user to define various firing scenarios assuming no feedback to the next charge by the rising tube temperature.

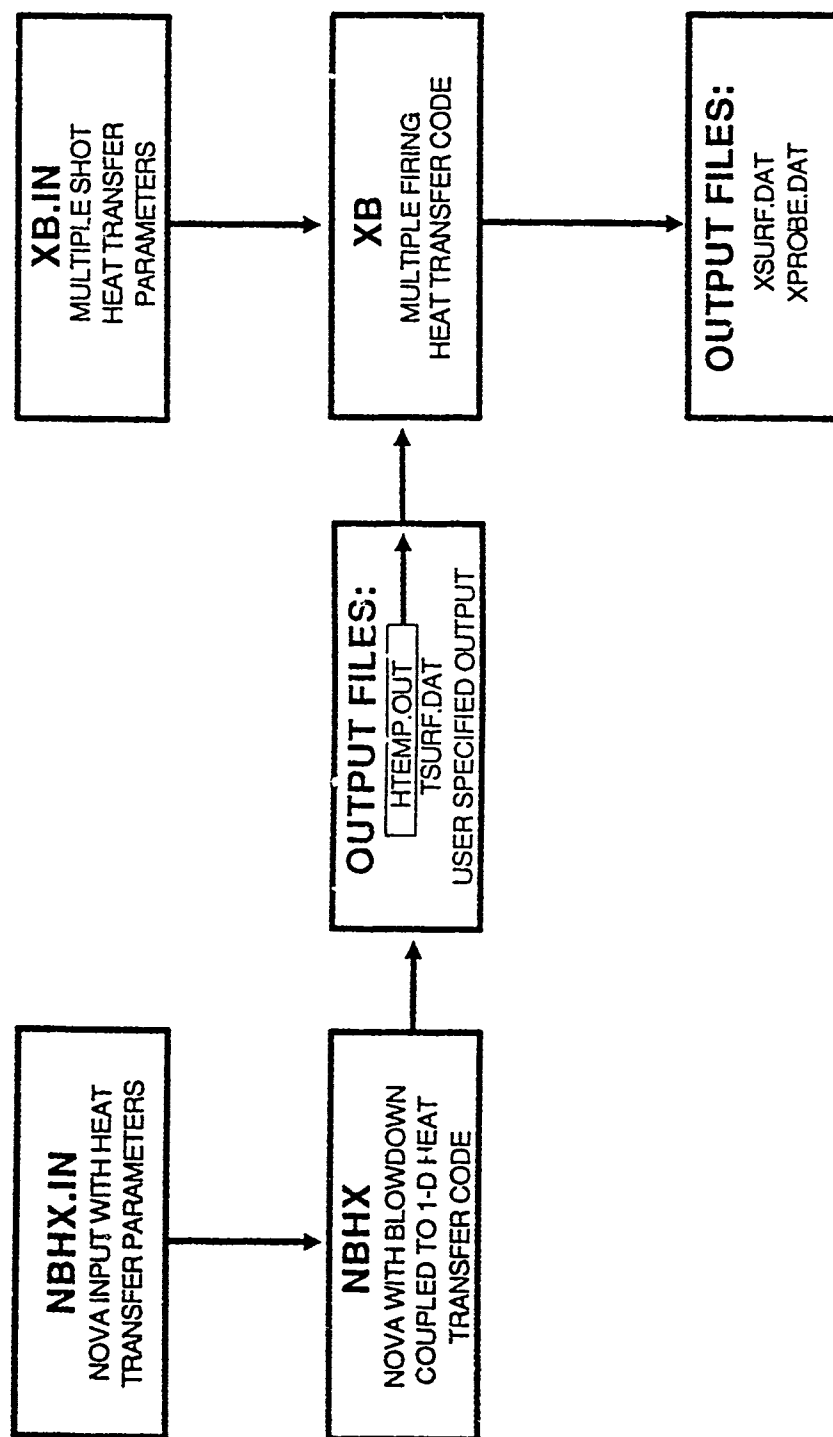


Figure 1. Heat Transfer Code Flow Chart.

3. NUMERICAL CALCULATIONS

There are two weapons systems for which experimental heating data exist; we chose to perform this study by modeling these two systems. One system involves the use of the M203 charge in a 155-mm howitzer; the other is a 27-mm caseless Olin round. The 1979 Thermal Warning Device (TWD) study by Vottis and Hasenbein (1979) provides the 155-mm data. The 27-mm charge (Williams 1972) presents a rapid, uniform rate of fire.

4. DISCUSSION

The M203 experimental data are presented in the TWD study in many forms with various rates of fire over periods of time. The scenario of 6 rounds per minute for 3 min followed by 3 rounds per minute continuous has been modeled and presented in Figure 2. A comparison of the experimental and numerical outer tube wall temperature history shown in Figure 3 has been made at the origin of rifling. This comparison reveals the importance of an external heat transfer coefficient if the calculation is to cover long periods of firing, for the temperatures keep rising while the experimental data level off. The temperature rise rate for the numerical calculation is about 1.8 times that of the experimental data. This causes the data presented here to be incorrect quantitatively, but qualitatively useful. There is a significant lag in the response of the outer tube wall from the first round for the numerical computations which reflects the amount of time for the heat to diffuse to the outer wall.

Two other scenarios performed on the M203 charge were 6 vs. 12 rounds per minute for 5 minutes and then 3 rounds minute thereafter for 100 rounds. The temperature was recorded at the origin of rifling. The results are presented for the inner and outer wall surface temperatures in Figures 4 and 5. The differences between 6 and 12 rounds per minute reveal themselves in the radial thermal profile of the gun tube over a period of time. Figure 6 shows the radial profile of the gun tube for three situations: 12 rounds per minute for 30 rounds and 6 rounds per minute for 15 and 30 rounds. What is seen between the two scenarios is that the tube's constant diffusivity does not transport the heat into the barrel as rapidly when the heat-flux rate at the inner wall is higher. This is true because a thermal barrier develops at the inner wall which prevents as much heat transfer to occur per round as that of the lower firing rate scenario. This shows that given a fixed number of rounds fired, the heat capacity of

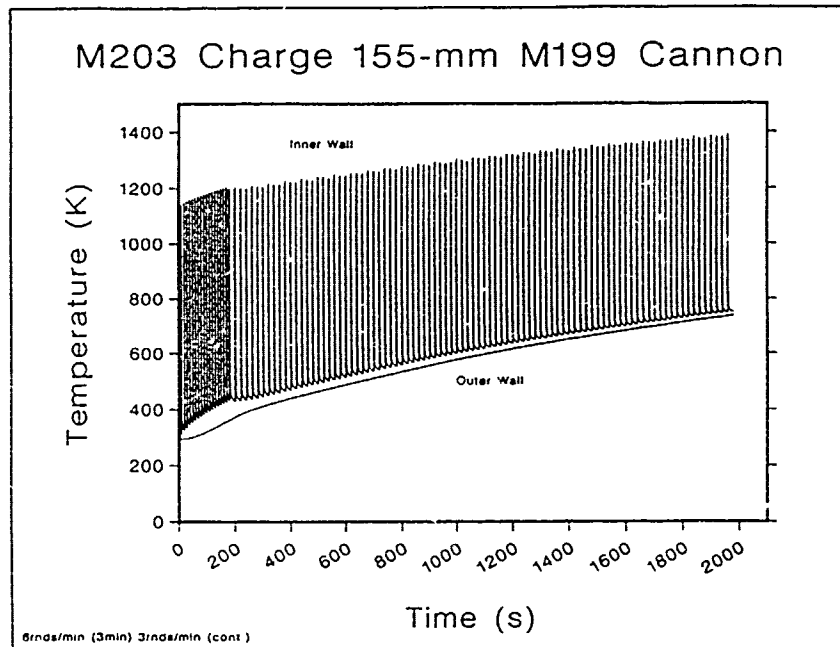


Figure 2. Numerical Gun Tube Temperature Calculation Results at Both the Inner and Outer Walls for the M203 Charge in a 155-mm Howitzer at the Origin of Rifling for 6 Rounds Per Minute for 3 Minutes Followed by 3 Rounds Per Minute Continuous.

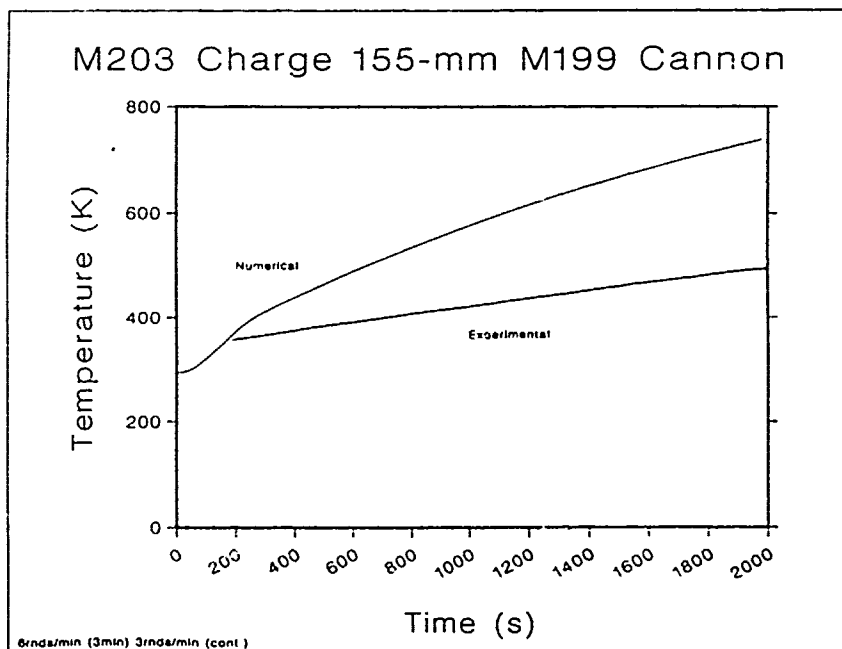


Figure 3. Experimental vs. Numerical Results for the Outer Gun Tube Temperature at the Origin of Rifling for the M203 Charge in a 155-mm Howitzer, Given the Firing Rate in Figure 2.

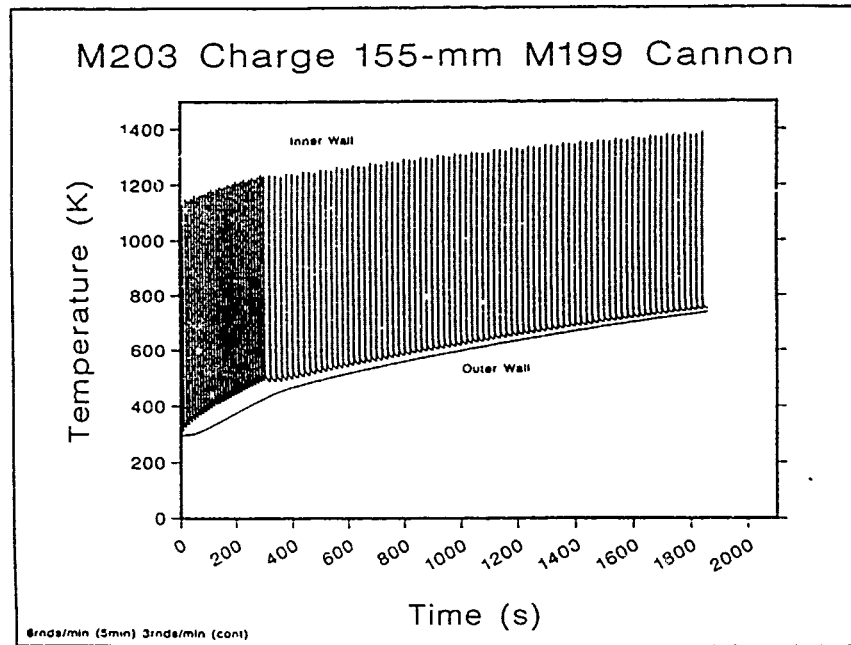


Figure 4. Numerical Gun Tube Temperature Calculation Results at Both the Inner and Outer Walls for the M203 Charge in a 155-mm Howitzer at the Origin of Rifling for 6 Rounds Per Minute for 5 Minutes Followed by 3 Rounds Per Minute Continuous.

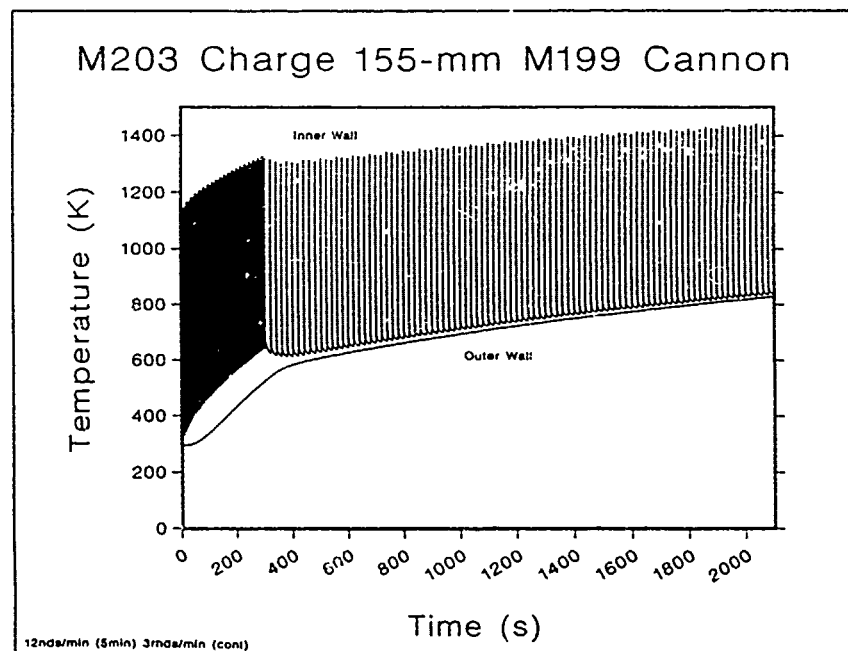


Figure 5. Numerical Gun Tube Temperature Calculation Results at Both the Inner and Outer Walls for the M203 Charge in a 155-mm Howitzer at the Origin of Rifling for 12 Rounds Per Minute for 5 Minutes Followed by 3 Rounds Per Minute Continuous.

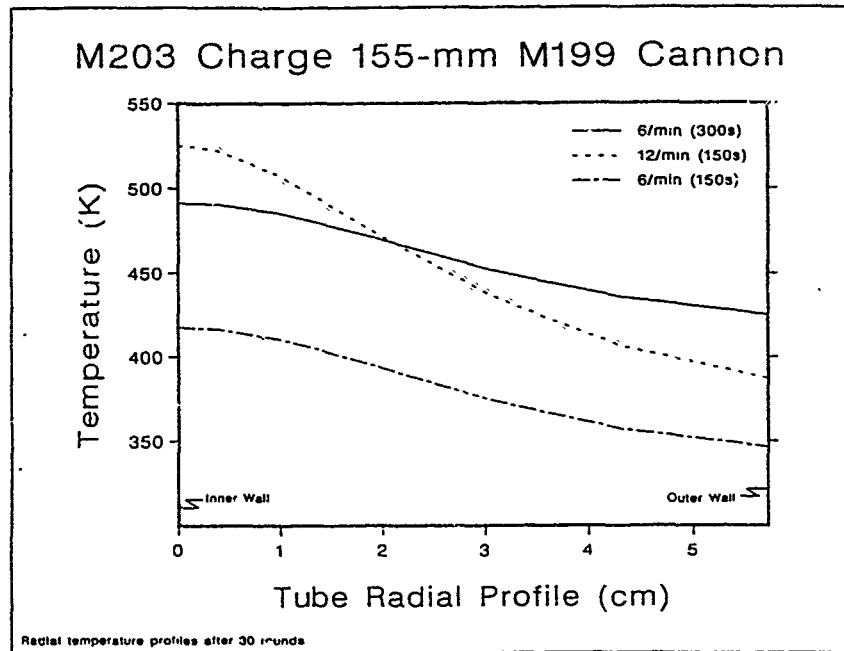


Figure 6. A Comparison of Wall Temperature Profiles for the 12 Rounds Per Minute vs. 6 Rounds Per Minute Scenarios After 30 Rounds and 6 Rounds Per Minute After 18 Rounds.

the tube near the inner wall is used under a relatively higher firing rate to store rather than transfer the energy, thus building a larger difference between the inner and outer wall temperatures (as seen in Figures 4 and 5) from 0 to 350 seconds. This difference decreases rapidly as the firing scenario is changed to the three rounds per minute sustained case, bringing the convection rate down closer to the conduction rate. Thus, after 110 rounds, both the 12 rounds per minute and 6 rounds per minute scenarios have the same thermal profile.

There is a 22.5-s lag in the response of the outer tube wall for the 6 rounds per minute and a 20.75-s lag for the 12 rounds per minute scenario. This reflects the amount of time for a thermal disturbance to propagate to the outer wall. The faster the firing rate, the higher the inner wall surface temperature and the larger the total thermal disturbance, but the rate of propagation does not present itself as a strong function of the firing rate. For linear conduction, the propagation rate is given by (Carslaw and Jaeger 1959)

$$a = \sqrt{\frac{2\omega k}{\rho C_p}} \quad , \quad (13)$$

with C_p being the specific heat of the barrel. The propagation rate is not so easily traceable analytically for radial systems with time-dependant boundary conditions. However, from the numerical experiment, it appears that a ratio difference of $10^{1/2}$, or about π , exists between the linear propagation function and that of the higher numerical result.

Figure 7 shows the experimental chamber and thermocouple placements for the 27-mm Caseless Automatic Weapon (CAW). The thermocouples were designed and built by Cornell Aeronautical Laboratory and placed between 0.0254 cm and 0.0508 cm away from the inner wall. Typical thermocouple traces are shown in Figure 8. What can be seen in Figure 8 is the convective nature of the heat transfer in that the recorded temperature decreases from the front of the chamber to the breech where the cross flow is small. The stop shoulder location was used for demonstrative modeling, the results of which are presented in Figure 9. The experimental and numerical peak temperatures match well after four rounds. The simulation models the experiment well because the outer barrel wall does not respond during the 3-s burst. There is a lag not numerically represented in the experimental data at the initiation of the burst. This could possibly be due to a small amount of ambient air surrounding the back side of the thermocouple acting as a heat sink, thus lowering the thermocouple's reading until the air became heated.

The rate dependency of the outer wall temperature shows the futility of using a TWD on the outer wall without the gun's recent firing history. A TWD could be very effective without any historical knowledge or tabularized data if it gave the inner tube wall temperature prior to loading.

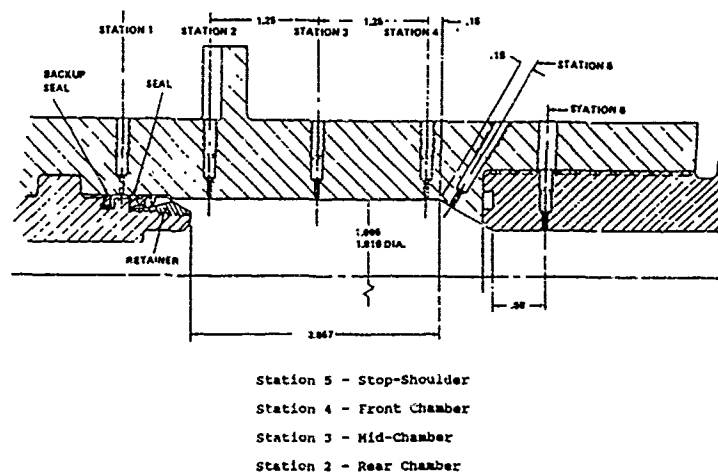


Figure 7. Experimental Location of the Thermocouples for the 27-mm CAW Study.

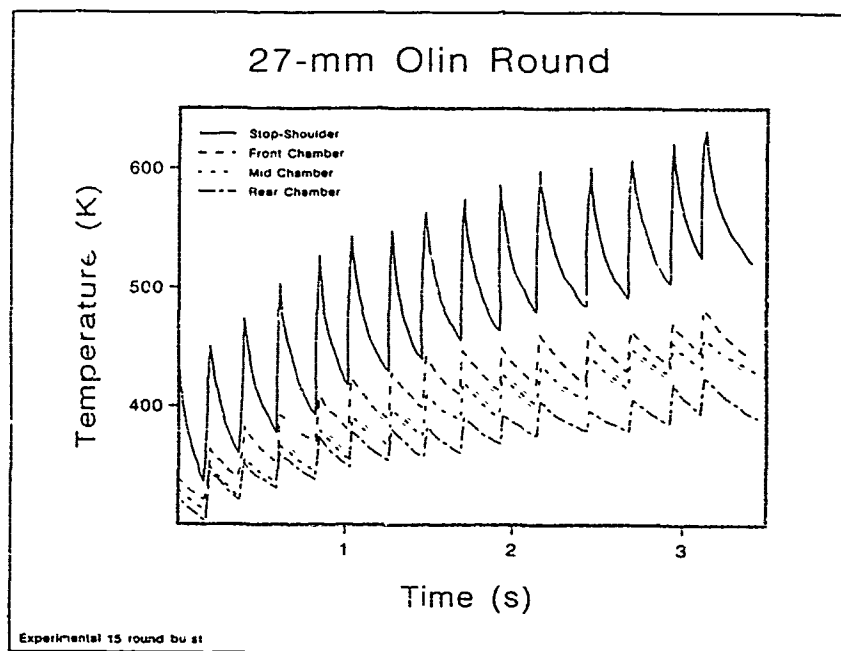


Figure 8. Typical Experimental Thermocouple Traces for the 27-mm CAW Study 0.000254 m (0.01 in) from the Inner Wall.

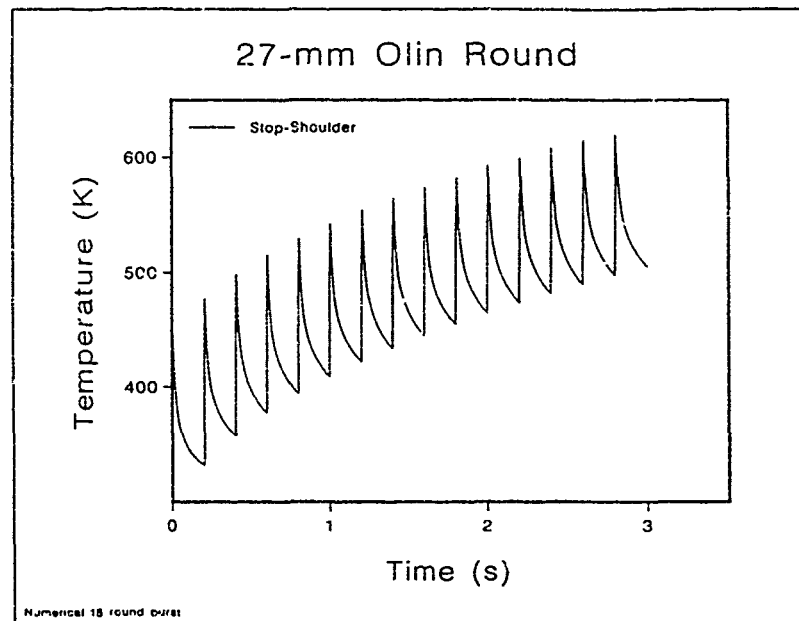


Figure 9. Numerical Results for the 27-mm CAW Study at the Stop Shoulder 0.0900254 m (0.01 in) From the Inner Wall.

5. CONCLUSIONS

A one-dimensional radial heat conduction code has been successfully coupled to a one-dimensional, two-phase flow IB code. The heat conduction code works fairly well during the initial temperature rise in a gun barrel as seen in the 27-mm data. Various scenarios for the 155-mm system qualitatively show the form of the gun tube's thermal profile. The results of the 155-mm study show that external heat transfer is needed if the long-term effects are to be quantitatively modeled.

6. CODE IMPROVEMENTS UNDER IMPLEMENTATION OR CONSIDERATION

The heat conduction analysis is currently being upgraded to a two-dimensional representation with internal radiation and external heat convection and radiation heat transfer models. The conduction and the internal wall heat transfer are being uncoupled to allow temporal and spatial heat convection coefficients and gas temperatures to be computed for use in other conduction codes in the community. Possible revisions include variable physical properties of the material, a more complex participating medium radiation model inside the gun tube, and coupling between the IB code and the heat conduction code for a more physically authentic calculation.

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LIST OF SYMBOLS

A_{ext}	-	Cross-sectional area at the muzzle
A_c	-	Critical cross-sectional area at the muzzle
b	-	Covolume equation constant
C_f	-	Skin friction coefficient
C_{fi}	-	Reference skin friction coefficient
C_p	-	Specific heat at constant pressure
g_o	-	Gravitational constant
h	-	Enthalpy
K	-	Conductivity coefficient
M	-	Mach number
\dot{M}	-	Mass flux
P_o	-	Reference pressure
P_z	-	Pressure at the z'th location
Q_w	-	Heat flux to the wall
R	-	Reynolds number
Re^*	-	Reference Reynolds number
R_g	-	Gas constant
T	-	Temperature
T^*	-	Static temperature
T_g	-	Gas temperature
T_o	-	Reference gas temperature
T_w	-	Wall temperature
u	-	Axial gas velocity

y	-	Covolume correction
z	-	Axial position
α	-	Thermal diffusivity
γ	-	Ratio of specific heats
μ^*	-	Reference viscosity
ρ	-	Density
ν^*	-	Reference kinematic viscosity
χ	-	Equivalent flat plate length
ω	-	Frequency of heat input

LIST OF ABBREVIATIONS

AFAS - Advanced Field Artillery System

IB - Interior Ballistic

TWD - Thermal Warning Device

CAW - Caseless Automatic Weapon

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